Azimuthal Anisotropy Measurements in PHENIX via Cumulants of Multi-particle Azimuthal Correlations

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Introduction

High energy-density nuclear matter is believed to be created in heavy ion collisions at RHIC. The statistical and dynamical properties of this matter is of great current interest.

- Azimuthal anisotropy (v_2) provides an important probe for high energy-density nuclear matter because it is sensitive to early pressure build-up in heavy-ion collisions. The development and dynamic evolution of this pressure is believed to be related to the the equation of state (EOS) and a possible phase transition.

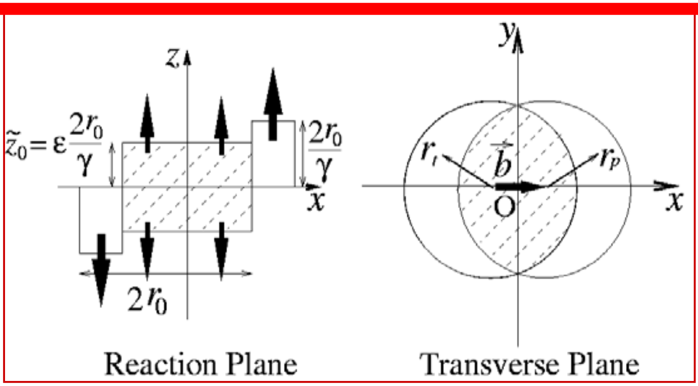


Fig. 1

Schematic view of a nuclear collision in the reaction plane (left) and transverse to the plane (right). Pressure gradients developed in the overlap region can lead to relatively strong momentum anisotropy.

- Detailed measurements of v_2 can:
  - **Provide an important probe for the EOS**
  - **Assist in discriminating between different sources of the anisotropy such as flow and jets**
  - **Validate and/or constrain models**

Common Methods for Anisotropy Measurements at RHIC

There are two main techniques which are commonly exploited to make anisotropy measurements at RHIC. Both are influenced by non-harmonic contributions.

1. **The reaction plane method:**

   - **This method involves an evaluation of the mean anisotropy of particles relative to an inferred reaction plane;**

$$\left\langle e^{2i(\phi - \phi_R)} \right\rangle_{events} = \left\langle \cos 2(\phi - \phi_R) \right\rangle_{events} = v_2$$

ϕ : **azimuth of particle** ϕ_R: **azimuth of reaction plane**

Application of a correction factor for reaction plane dispersion is required to obtain accurate anisotropy values.

2. **The method of two particle correlation functions:**

   - **This method involves an evaluation of the mean anisotropy between particle pairs;**

$$\left\langle e^{in(\phi_1 - \phi_2)} \right\rangle = \left\langle e^{in(\phi_1 - \phi_R)} \right\rangle \left\langle e^{in(\phi_R - \phi_2)} \right\rangle + \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle_c$$

$$= v_2^2 + O\left(\frac{1}{M}\right)$$

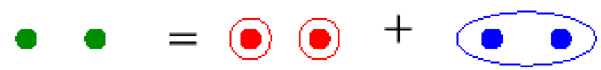
no correction factor is required

Cumulant Method (2nd order)

Analysis Method

This analysis exploits the cumulant method of
Borghini, Dinh and Ollitrault (Phys.Rev.C 64 054901 (2001)
to make detailed differential measurements of v_2. That is, flow harmonics are calculated via the cumulants of multiparticle azimuthal correlations and non-flow contributions are removed by higher order cumulants.

Two-particle correlations can be decomposed into a harmonic and a non-harmonic term (hereafter termed flow and non-flow).



$$\left\langle e^{in(\varphi_1-\varphi_2)}\right\rangle_m = v_n^2 + \left\langle e^{in(\varphi_1-\varphi_2)}\right\rangle_c$$

Thus, the second order cumulant can be written as;

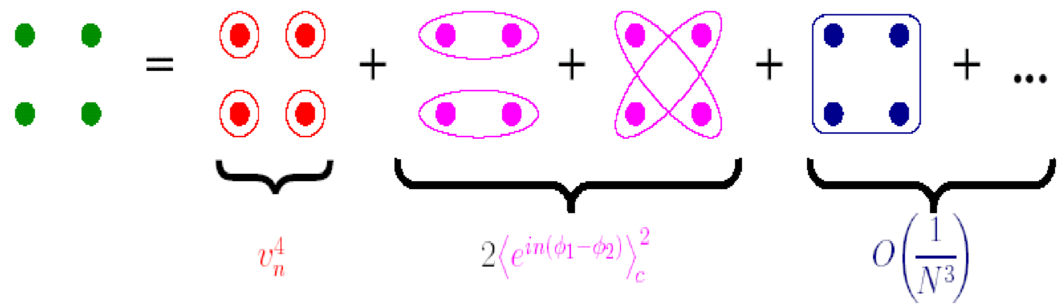
$$C_2\{2\} = \langle\langle e^{2i(\phi_1-\phi_2)}\rangle\rangle = v_2^2 + \langle e^{2i(\phi_1-\phi_2)}\rangle_c \quad (1)$$

and is relatively straightforward to evaluate.

Cumulant Method (4th order)

If flow predominates, cumulants of higher order can be used to reduce non-flow contributions

- **Following the decomposition strategy presented earlier for two-particle correlations, the 4 particle correlations can be similarly decomposed as follows:**



$$C_n\{4\} = \left\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\right\rangle - \left\langle e^{in(\varphi_1-\varphi_2)}\right\rangle\left\langle e^{in(\varphi_3-\varphi_4)}\right\rangle - \left\langle e^{in(\varphi_1-\varphi_4)}\right\rangle\left\langle e^{in(\varphi_3-\varphi_2)}\right\rangle$$

$$\langle\langle e^{2i(\phi_1-\phi_2+\phi_3-\phi_4)}\rangle\rangle \equiv \langle e^{2i(\phi_1-\phi_2+\phi_3-\phi_4)}\rangle - 2\langle e^{2i(\phi_1-\phi_2)}\rangle^2$$

$$= -v_2^4 + O\left(\frac{1}{M^3}\right)$$

Improved accuracy is clearly achieved if $v_2 \gg \frac{1}{M^{3/4}}$

Data Analysis Procedure (I)

PHENIX Detector - Second Year Physics Run

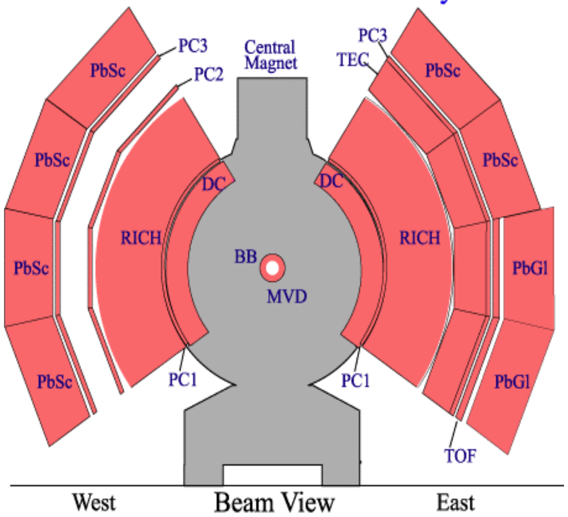


Fig. 2

Cumulant analysis in PHENIX Follows three basic steps.

I. Track selection
II. Evaluation of the cumulants
III. Application of an acceptance correction

Track Selection

- **Event selection:**
  - 22.3 M minimum bias Au+Au (200 GeV) events
- **Tracks reconstructed using**

  Drift Chamber (DC),
  PadChamber1 (PC1)
  PadChamber3 (PC3)

Track Selection:

- Good quality tracks
- 2σ PC3 matching to reduce background
- Transverse momentum cut:

  0.3-2.0 GeV/c for integral
  0.3-4.0 GeV/c for differential

Data Analysis Procedure (cumulant generation)

II. Cumulants for the integral and differential flow are generated via generating functions

$$C_2(x,y) = M\left(\langle G_2(x,y)\rangle^{\frac{1}{M}} - 1\right)$$

Integral flow

$$D_2(x,y) = \frac{\langle e^{2i\psi} G_2(x,y)\rangle}{\langle G_2(x,y)\rangle}$$

Differential flow

where

$$G_2(x,y) = \prod_{j=1}^{M}\left(1 + \frac{2x\cos 2\phi_j + 2y\sin 2\phi_j}{M}\right)$$

and ψ is the azimuth of a particle in the p_T window of interest

- **A fixed number (M) of particles is selected at random to generate cumulants for integral flow to avoid errors due to multiplicity fluctuations**
- **Particles for integral flow chosen outside of the (p_T, η) window of interest to avoid autocorrelations**

Data Analysis Procedure (acceptance/efficiency correction)

The anisotropy is corrected for acceptance/efficiency via a Fourier series expansion of the PHENIX azimuthal acceptance:

$$A(\phi) = \sum_{k=-\infty}^{k=+\infty} a_k e^{ik\phi}$$

A non-isotropic acceptance, as in the PHENIX detector, entails a mixing of different harmonics, and hence leads to modified relations between cumulants and flow

- For instance, for the 2nd order cumulant

$$c_2\{2\} = v_2^2$$ **for a perfect acceptance**

becomes $$c_2\{2\} = k_1 v_1^2 + k_2 v_2^2$$ **for a non-perfect acceptance**

where k_1 and k_2 are functions of the Fourier coefficients a_k

- Similarly

$$c_1\{2\} = k_1' v_1^2 + k_2' v_2^2$$

- Combining the equations above gives v_2 in terms of $c_1\{2\}$ and $c_2\{2\}$

Test Demonstration of the Robustness of the Analysis Procedure

A cumulant analysis in PHENIX is non-trivial, primarily because of the relatively limited acceptance of the device. This being the case, it is important to demonstrate the reliability of our extraction procedure.

- **Monte Carlo simulation tests were performed with known v_2 and the PHENIX acceptance as input**
- **Generated events were then analyzed through our analysis framework.**
- **The results from these tests show that the v_2 extracted is robust and acceptance corrections are very well implemented**

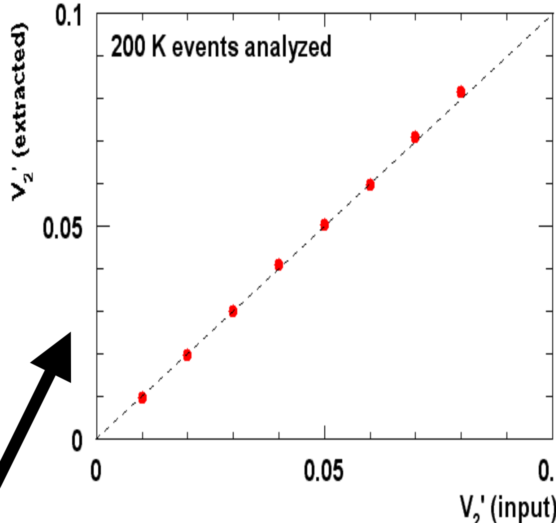


Fig. 3

Input vs. output v_2 from simulations

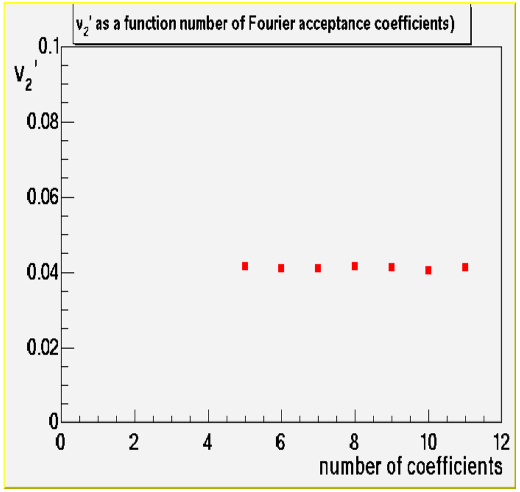


Fig. 4

v_2 vs. number of Fourier coefficients used for acceptance correction

Experimental Results (pT and centrality dependence)

The cumulant method has been used to make very detailed studies of the anisotropy as a function of

- centrality
- pseudo-rapidity
- Transverse momentum (pT)
- pT and centrality
- pT of the particles used to construct integral flow etc..

In the following, several representative results are shown.

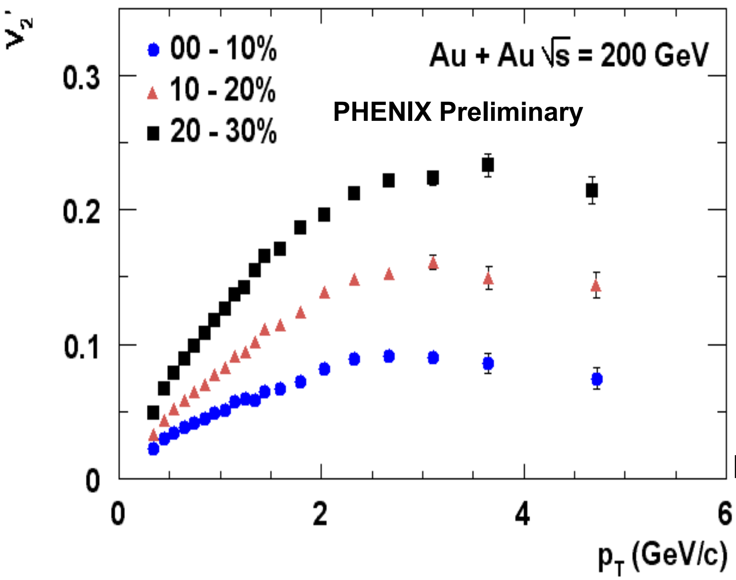


Fig. 5

The pT dependence of v_2 show:

- **Saturation for pT > 2 GeV/c**
- **Increases with centrality and pT**

High pT particles which are dominantly from jets are clearly correlated with low pT particles which are thought to be associated with softer processes.

Experimental Results (pseudo-rapidity dependence)

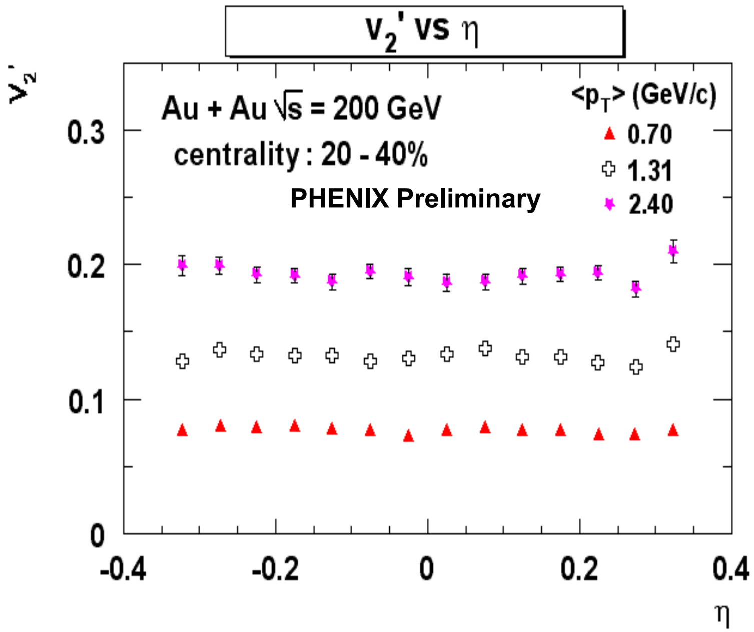


Fig. 6

• **The pseudo-rapidity dependence of V2 (for several pT selections) is essentially flat within the PHENIX acceptance.**

Comparison between methods

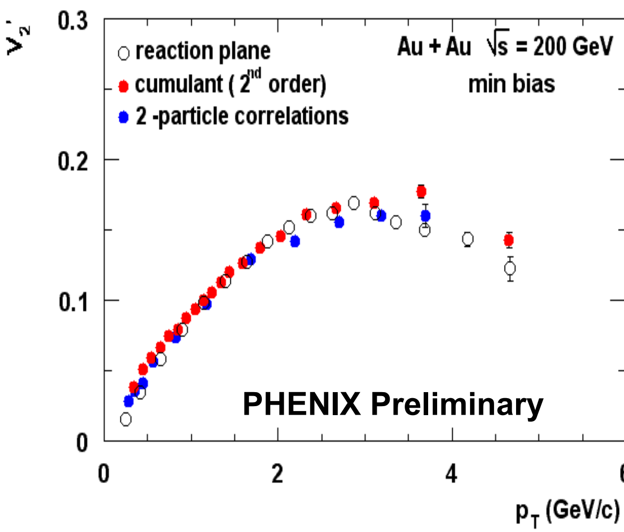


Fig. 7

- Relatively good agreement is found between values obtained from second order cumulants and those obtained from the reaction plane and two particle correlation function methods.
- Small deviations for pT > 3 GeV/c may be due to an increase in the influence of jets.

Experimental Results (dependence on pT of the Reference)

Given the fact that soft processes are expected to dominate at low pT and harder processes at higher pT, v_2 was extracted for several different pT reference

- No significant dependence on the p_T of reference is observed for pT < 2 Gev/c
- For pT > 2.5 GeV/c, the trend is compatible with an increase in the jet contribution to the anisotropy.

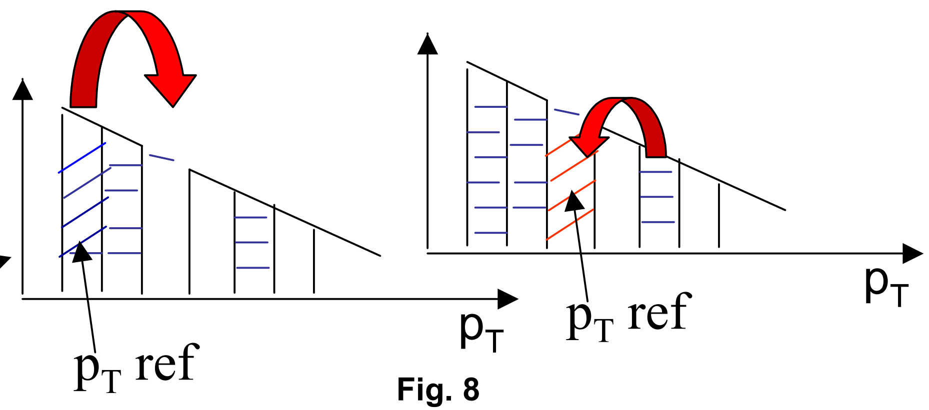


Fig. 8

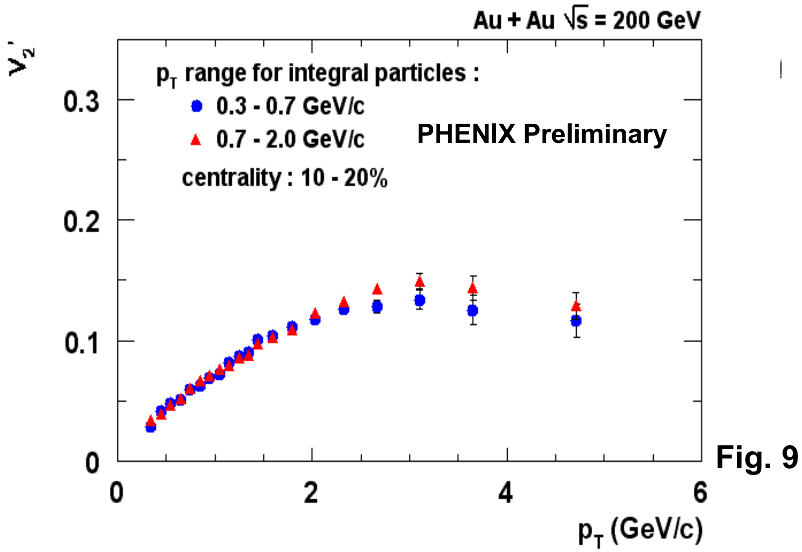
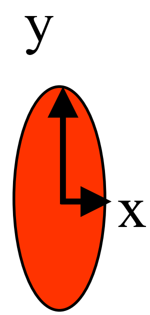


Fig. 9

Experimental Results (Centrality dependence)



eccentricity

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Anisotropy can result from hydro-like flow and jet-quenching. In both of these cases, the initial eccentricity is a major driving force for the anisotropy.

- For eccentricity driven anisotropy, a rather specific centrality dependence is predicted. Namely, v_2 should follow the variation of eccentricity with N_{part} and show eccentricity scaling.

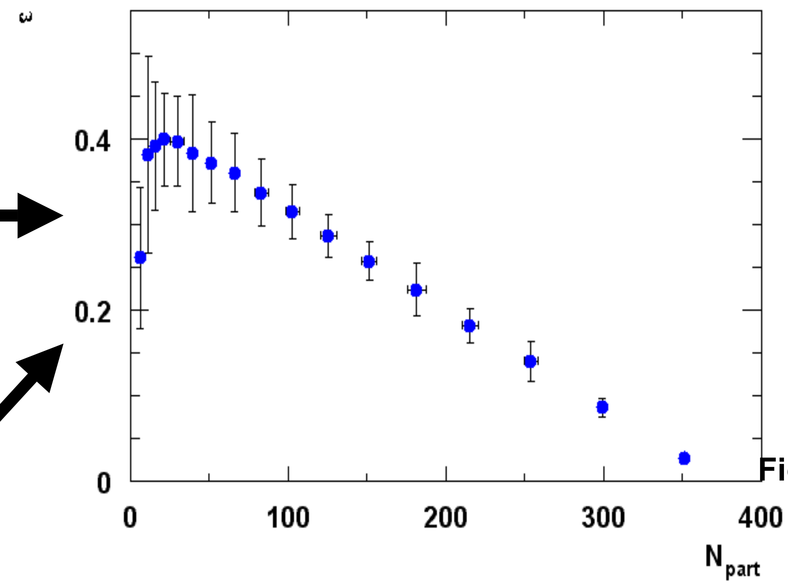


Fig. 10

Variation of eccentricity with number of participants based on a Glauber model

Experimental Results (Test of eccentricity scaling)

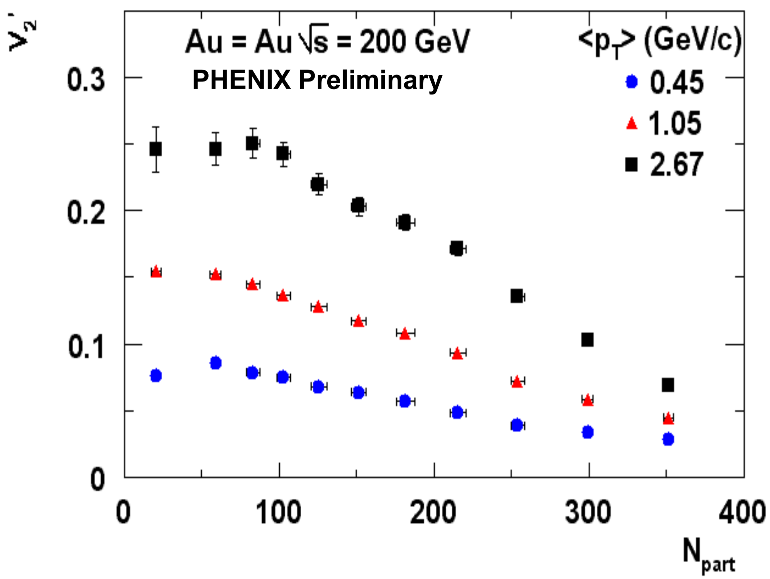


Fig. 11

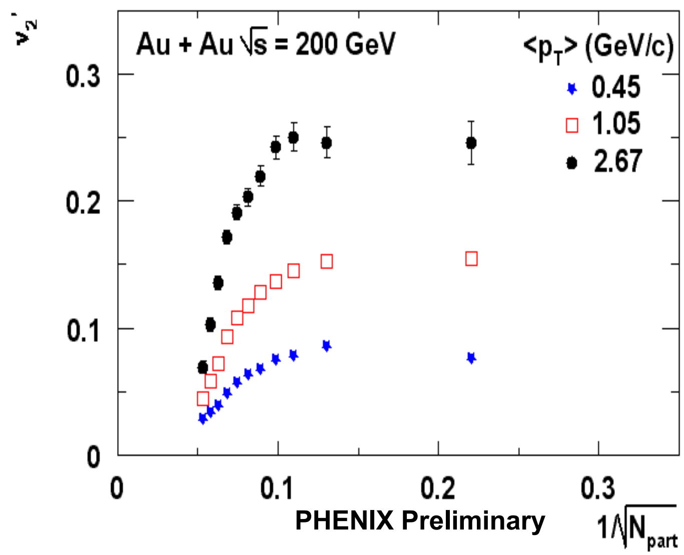


Fig. 12

- => The centrality dependence observed for both high and low pT particles follow the same patterns which are strikingly similar to the expected dependence shown in Fig. 10.

- Models based on minijet production predict that v_2 should scale with $1/\sqrt{Npart}$

- => Fig. 12 indicates that the data is compatible with this scenario only for a limited range of centralities

Experimental Results (Further Tests of eccentricity scaling)

If the initial eccentricity is a major driving force for the anisotropy. Then one expects approximate eccentricity scaling.

- Since the integral anisotropy is proportional to the eccentricity, one can scale by this integral

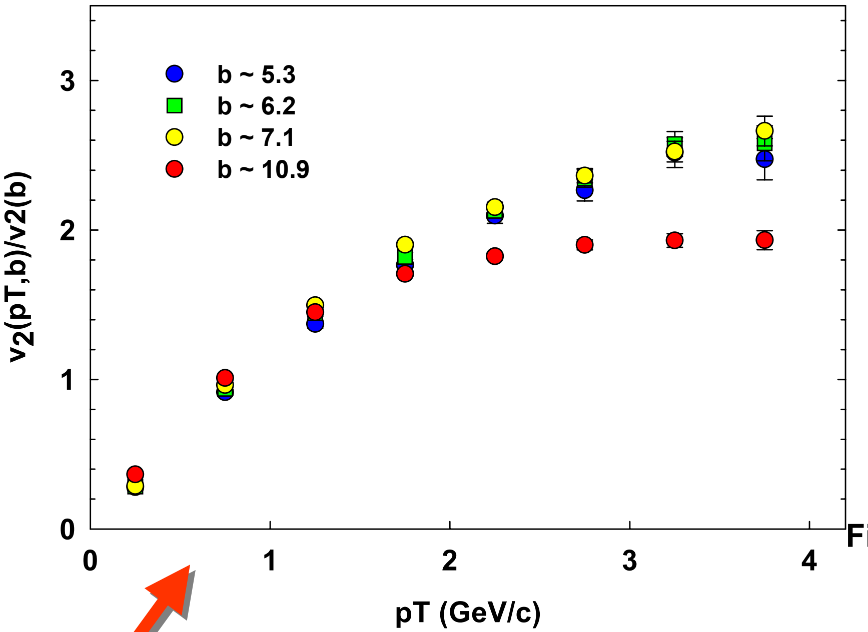


Fig. 13

- This scaling [of the anisotropy] is observed for a broad range of centralities in the model of Molnar et al. (Nucl. Phys. A697, 495, 2002) if large opacities are assumed.

Experimental Results (Tests of eccentricity scaling)

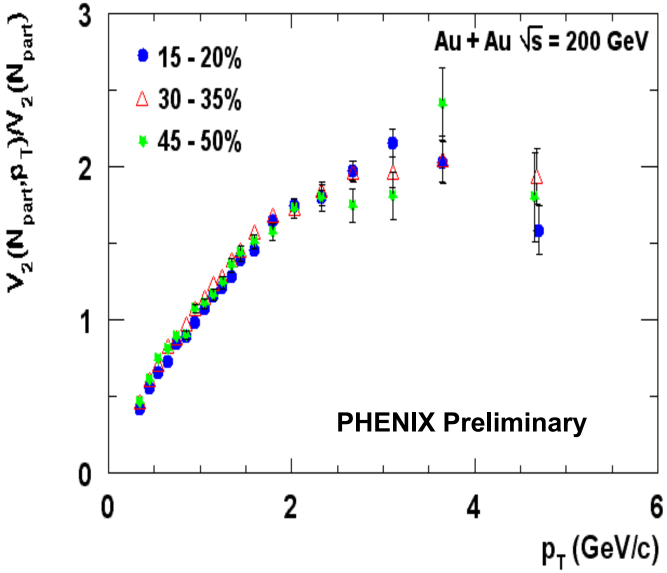
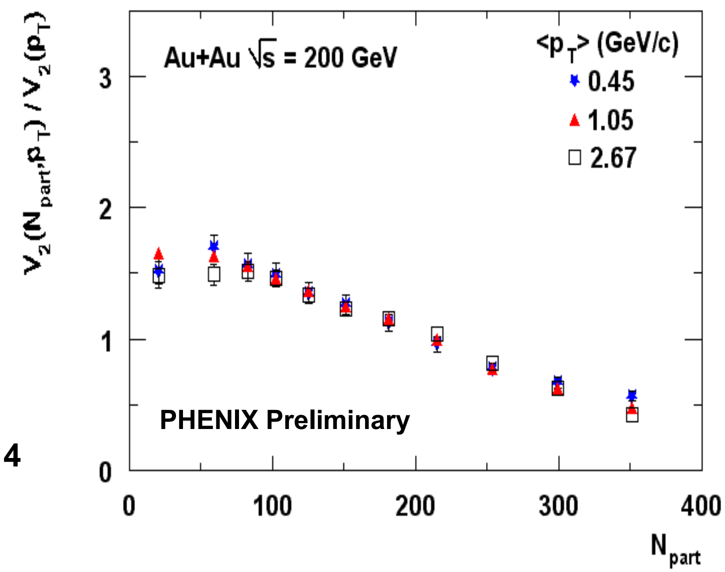


Fig. 14



- The data indicates that the differential anisotropy scales with the integral anisotropy.
- Scaling property holds for both high and low p_T particles. If jets dominate high pT particles then jet quenching could lead to the observed scaling for these particles.

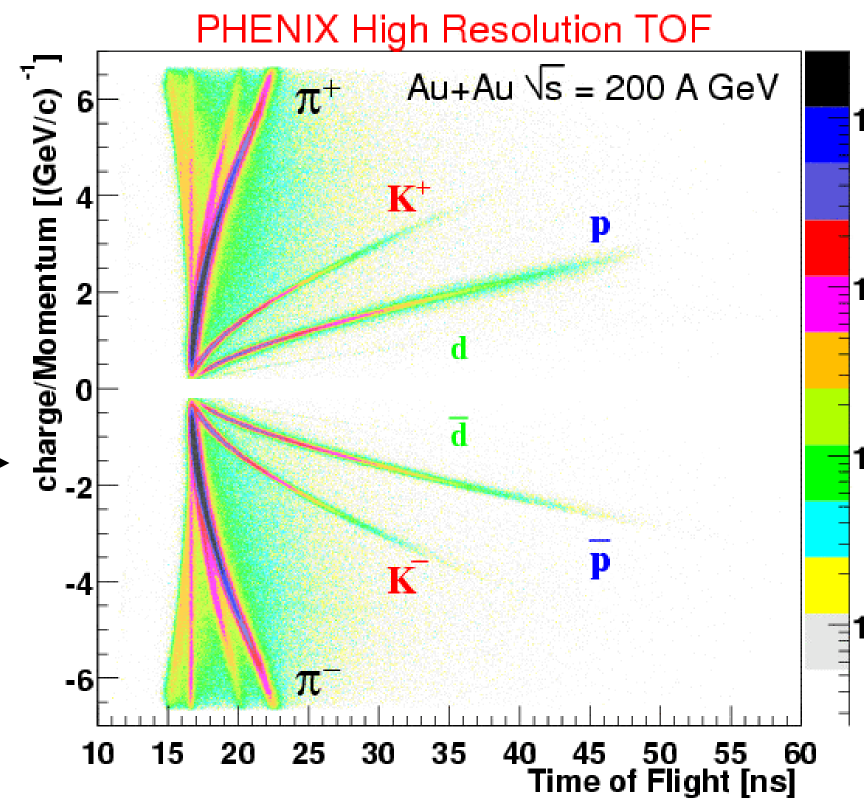
The observed scaling property also suggest a factorization of the anisotropy.

$$v_2\,(b,p_T) \approx v_2(b)\,v_2(p_T)$$

Ongoing analysis

It is also important to study the flavor dependence of the anisotropy.

• Good particle identification is achieved in the PHENIX TOF and EMCAL respectively



Ongoing analyses focus on: measuring v_2 of identified hadrons using the TOF and Electromagnetic Calorimeter (EMCAL)

Summary / Conclusion

- **Detailed** differential azimuthal anisotropy measurements have been made with PHENIX via cumulants of azimuthal correlations.

- These measurements indicate that:

  - High & low p_T particles are correlated

  - v_2 is essentially independent of $p_{T\ ref}$

  - $v_2(b,p_T)$ factorizes in $v_2(b)v_2(p_T)$

  - There appears to be eccentricity scaling of v_2 at high p_T

These results are compatible with correlation of jets with the reaction plane, as would be expected from jet quenching